NASA/CR-97- 208175

IN-91-CR
137220

Final Technical Report on NASA Grant NAGW-4035

"Numerical Simulation of Rotation-Driven Plasma Transport in the Jovian Magnetosphere"

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Period of Grant: April 1, 1994 to December 31, 1997

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Work Accomplished

Background

A Jupiter version of the Rice Convection Model (RCM-J) was developed with support of an earlier NASA SR&T grant. The conversion from Earth to Jupiter included adding currents driven by centrifugal force, reversing the planetary magnetic field, and rescaling various parameters. A series of informative runs was carried out (*Yang et al.*, 1992a,b, 1994), all of them solving initial value problems. The simulations followed an initial plasma torus configuration as it fell apart by interchange instability. Some conclusions from the simulations were the following:

1. We confirmed that, for conventional values of the torus density and ionospheric conductance, the torus disintegrates by interchange instability on a time scale of ~ one day, which is 1-2 orders of magnitude shorter than the best estimates of the average residence time of plasma in the torus.
2. In the model, the instability could be slowed to an arbitrary degree by the addition of sufficient impounding energetic particles, as suggested earlier by *Siscoe et al.* (1981). However, the observed energetic particles do not seem sufficient to guarantee impoundment (e.g., *Mauk et al.*, 1996).
3. Whether inhibited by impoundment or not, the interchange was found to proceed by the formation of long fingers, which get thinner as they get longer. This picture differed dramatically from the conventional radial-diffusion picture (e.g., *Siscoe and Summers* (1981)), more superficially with the outward-moving-blob picture (*Pontius and Hill*, 1989).

The obvious limitation of the original RCM-J was that it could not represent a plasma source. We could represent the decay of a pre-existing torus, but we could not represent the way ionization of material from Io continually replenishes the plasma. We consequently were precluded from studying a whole set of fundamental issues of torus theory, including whether the system can come to a steady state.

Unfortunately, the plasma source could not be added to the RCM-J just by making up an appropriate source function, because the basic way in which the Rice Convection Model represented particles did not allow incorporation of a source. Specifically, the RCM's numerical procedure makes use of the fact that, in the absence of sources and sinks, η, which is the number of charged particles of a given type per unit magnetic flux, is constant along the drift path of such a particle. Thus if a flux tube initially has a certain content η, it will forever have that content. Under these circumstances, a contour of constant η follows the same equation of motion as a drifting particle. Therefore, the RCM represents each contour of constant η by a series of test particles, and we follow the time evolution of the contour as the test particles drift in the self-consistently computed electric field and assumed magnetic field. Instead of characterizing the distribution of η basically in terms of values at grid points, we characterize it in terms of the contours of constant η. This numerical method has been well proven in years of RCM operations. It avoids the numerical diffusion, overshoots, and oscillations that are characteristic of grid-based algorithms in the presence of sharp density jumps, which are characteristic of the magnetospheres of both Earth and Jupiter. It also provides an elegant and precise way to calculate Birkeland currents (*Harel et al.*, 1981), superior to grid-based calculations of the Birkeland current, which, in the RCM context, are typically irregular and noisy. The shortcoming of the contour-based particle representation is that there is no simple way to incorporate a plasma source. Thus incorporation of a source for the Io plasma requires a deep rewrite of the computational machinery that keeps track of particle populations in the RCM.

New Version of the Rice Convection Model that can Incorporate Sources

We designed a two-tiered computational scheme that promised to combine the advantages of the contour-based RCM representation (no numerical diffusion or oscillation, precise calculation of Birkeland current) with the advantages of the grid-based system (easy inclusion of sources and losses). The disadvantage of the new scheme is that it is complicated. The main part of the density calculation is done in terms of contours of constant η, as in the traditional RCM, but the effects of sources and losses on the plasma densities are separately computed on a grid. The two density computations – one based on a grid and one on contours – are carried on in parallel for a time period ΔT that is long compared to a model time step (seconds) but short compared to the loss lifetime or the time required for the source to cause a major change in the density. Then the two parallel computations are stopped. The edge-based densities are converted to grid-based densities, and the two parts are added together. The resulting total distribution is then recontoured, and the grid-based density is set to zero. Then the main calculation resumes for the next period ΔT. The recontouring is carried out on an adjustable grid that is much finer than the main computational grid, which allows us to keep as much fine structure as we want and keep numerical diffusion to a low level.

Completion of a working RCM-J based on this algorithm has taken longer than we originally expected, for two principal reasons:

1. We underestimated the difficulty of designing, programming, and implementing the new algorithm in the RCM. Complications arose mostly from the requirement that the approach be adequate for modeling Earth as well as Jupiter. Much of the work that we are doing now with the Earth-based RCM involves embedding it in models that have larger modeling domains, either global MHD models or a magnetospheric-equilibrium solver. This requires that the RCM's outer-boundary location, as well as the boundary-condition particle pressure and temperature, change with time. This situation is difficult to handle in the context of the traditional, contour-based RCM. However, we realized that it could be accomodated within the context of the two-tier RCM. Though the two-tier RCM was originally conceived for modeling the Jupiter plasma torus, we realized that, with some effort, it could be made general enough to handle moving boundaries and changing boundary conditions. Although this made the job substantially more complicated, it also allowed us to use some Earth-associated funding in the development of the algorithm.

2. Fluctuations in our group's overall funding level decreased the efficiency of the programming effort on this project. In the mid-nineties, our funding level was high, and Bob Spiro, our group's lead programmer, who wrote the RCM code as well as the DoD-supported Magnetospheric Specification Model (MSM), had to concentrate his efforts on MSM in order to meet strict DoD contract deadlines. To fill this hole, we hired Yong-Shiang Yang, who had done his thesis on the RCM-J, to program the new two-tiered RCM. He got half-way through the job before leaving for greener pastures in the oil industry. Next, we hired Ken Nishikawa, who had had long experience in computational physics, to complete the task. This move was only marginally effective and Ken left the group within a year. Late last year, Bob Spiro returned to the task, and we feel we are now

back on track. Unfortunately, the fact that we had three scientific programmers working on the problem, in succession, reduced the efficiency of the very complicated programming effort.

Bob Spiro has now finished programming the two-tiered RCM, and the central component of the new code has been thoroughly tested. The next task is testing of the fully assembled two-tier RCM. Once that is done, we plan to do the first set of Jupiter simulations with an Io-associated plasma source. If all goes according to plan, we should have a good set of new Io-torus simulations done before the deadline for SR&T proposals in summer 1998, in which case we will submit a proposal to continue this work and to carry out new torus simulations with the powerful new code. In collaboration with Bill Smyth (AER), we plan to incorporate into the new RCM-J a quite realistic representation of the Io source, and we envisage an extremely illuminating series of simulations that explore the basic structure and dynamics of the torus.

Simulations of the Effect of Differential Rotation

With support from grant NAGW-4035, we carried out some very informative torus simulations with the old RCM-J, without sources. The results are described in the following paper

Pontius, D. H., Jr., R. A. Wolf, T. W. Hill, R. W. Spiro, Y. S. Yang , and W. H. Smyth, Velocity shear impoundment of the Io plasma torus, accepted for publication in *J. Geophys. Res.*, 1998.

The torus exhibits a velocity shear that is easy to understand. When a new torus ion is created from photoionization of a torus neutral, its azimuthal velocity must increase from the Kepler velocity to the much faster **E×B** drift velocity of the plasma torus. The associated angular momentum comes from Jupiter's ionosphere and the associated atmospheric neutrals. Consequently, the part of Jupiter's ionosphere and upper atmosphere that maps to the torus must rotate more slowly than the surrounding planetary atmosphere, having been slowed by the continual drag force. Consequently, the corotation lag is largest in the part of the plasma torus that is being replenished by photoionization, and there is a consequent strong velocity shear in the inner part of the torus.

Using both an analytic argument and RCM-J simulations, *Pontius et al.* (1998) showed that this velocity shear can dramatically inhibit the interchange instability in the inner torus. The velocity shear bends the outreaching interchange fingers almost 90°, reducing their rate of development and nearly eliminating their effect on radial transport. I believe that this rotational shear is essentially what holds the inner plasma torus together, allowing ion residence times ~ 100 days, when simple application of interchange-instability theory gives growth rates ~ 1/day. Therefore, I think that the *Pontius et al.* (1998) paper answers the longstanding basic question of what confines the Io plasma torus.

It is interesting that an analogous kind of velocity-shear stabilization is currently viewed as the most promising avenue to achieving long confinement times in magnetically confined fusion plasmas (*Burrell*, 1997).

Summary Comments

We have put a great deal of effort into development of a powerful new Jupiter version of the Rice Convection Model that can explicitly include an Io-associated plasma source. It will be capable of new series of computer simulations that should provide much better understanding of the structure and dynamics of the torus. We have also demonstrated that velocity shear in the inner torus is probably what holds the inner torus together.

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